# Product Identity and Its Impact on Discrete Event Observability

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## Abstract

Sensing of the specific identity of products moving through the manufacturing supply chain is typically indirect. Usually, such information is inferred from local proximity data coupled with appropriate computer based tracking models which align this data to the last known point of identity recognition. So-called *Automated Identification* systems promise to address some of the limitations of these approaches by providing automated, ubiquitous, item level product identity information at any point in the supply chain. One interpretation of the impact of such a facility is in terms of the enhanced observability of the (discrete-event) state space which represents the production, storage, transportation and retail processes to which a product is subject during its life cycle. This paper examines this extended notion of observability and illustrates its impact on physical systems represented by such discrete event systems via a materials handling example. Practical implications for industrial control are also considered.

## 1. Introduction

Direct product sensing is often replaced in industrial applications with inferred information about product state derived indirectly from process conditions, and a suitable control strategy is executed on the basis of this information. Temperature, location and pressure are commonly used process indicators used to infer product properties.

The focus of this paper is to introduce the notion of the direct sensing of product identity within the manufacturing supply chain. Direct product identity sensing (or *automated identification*) involves the automated, timely recording of an identity record for a particular product. Coupled with suitable location information, this record can enable actions to be taken which are specifically relevant to the item in question. The specific aim of the paper is to examine the impact of product identity information on the observability of the underlying discrete event system, its ability in (discrete event) control systems to improve the fidelity of observations made, and hence also the subsequent control actions. In the case of an automotive plant for example, automated identification enables individual cars to be tracked throughout their production life, and for production control actions to be made specific to their individual order requirement.

In the next section the main features of Auto ID systems are overviewed. We then examine automated identification in the context of a discrete event modelling formalism, and show that the impact of product identity data can be shown to increase the observable state space - or alternatively that it reduces the so called observability mask – a projection from the operational state space onto the supervisor state space (Kumar, Cassandras, 1999). It is intended that such an abstract interpretation will enable the results to be used broadly in the design and operation of industrial systems, and the paper is concluded with some comments specifically for industrial adoption.

## 2. Automated Identification (Auto ID) Systems

### 2.1 Overview

Monitoring of the specific identity of products moving through the manufacturing supply chain is typically indirect. Such information is inferred from local proximity data coupled with appropriate computer based tracking models which align this data to the last known point of identity recognition. Often this identity recognition process involves a manual inspection or a bar code scan – also often manually taken. The limitations in using such systems as a means of tracking individual items during their life cycle are:

- there are significant inaccuracies associated with the initial product identification process, which become exacerbated as the product evolves over time
- the identification processes are cumbersome and difficult to fully automate in a timely manner
- typically, the identification processes identify - at best - product type but not in fact the unique identity of the instance of the product in question

This leads to the concept of so called *automated identification* systems which for the purposes of this paper can be defined:

**Definition 2.1** **[**Automated Identification]

*Automated identification involves the automated extraction of identity of an object*

## 2.2 Auto ID Systems

Automated identification systems have been used industrially for almost twenty years. More recently the aim of the work of the Auto ID Center – see www.autoidcenter.org – has been to develop standards and network infrastructure for enabling unique, item level identity and related product information to be uniformly available to enhance production, distribution, storage and retail processes in the supply chain (Sarma, 1999). The Center is also helping to bring the price of the automated identification process down so that it becomes feasible to consider the automated identification of everyday retail items. The initial systems being developed draw heavily on past and current developments in the area of Radio Frequency Identification (RFID) – see (Finkenzeller, 1999) and the references therein. RFID provides a simple means of obtaining unique, item level identity data, increasingly at a reasonably low cost. (Sarma, 2002) These systems can be coupled to networked data bases which enable additional data to be held about the item.

A simple overview of a typical Auto ID system is now provided. The intention here is not to provide a definitive description – the reader is referred to (Sarma, 1999). Referring to Figure 1 we note the following features:

1. An identity tag attached to a product with a chip capable of storing a unique identification number and communicating this number via an RFID communication system.
2. Networked RFID readers and data processing system capable of collecting signals from multiple tags at high speed (100s per second) and of pre-processing this data in order to eliminate duplications and misreads.
3. One or more networked data bases storing information related to the product (basic product data, tracking history, processing instructions) whose entries are uniquely bound to the product identification number.

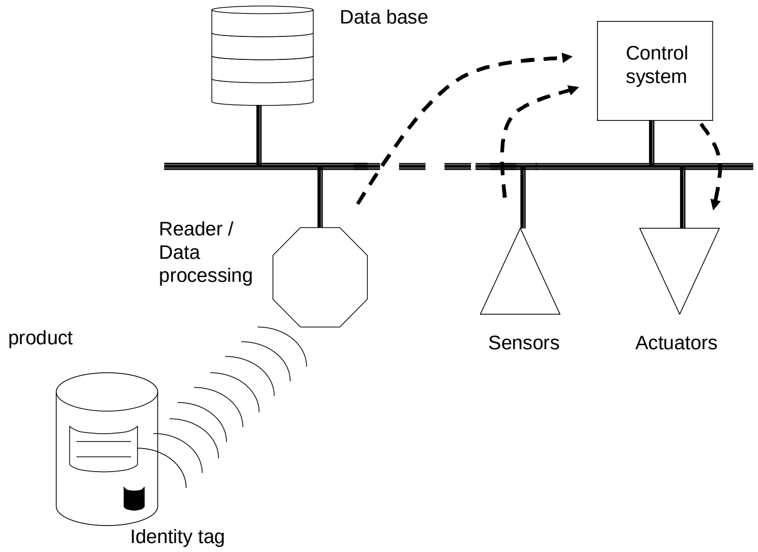

**Figure 1   Simple Schematic of an Auto ID System**

### 2.3 Impact on Industrial Control

Initially, the simplest benefits from the deployment of Auto ID systems in the manufacturing supply chain will be to improve tracking and hence a product's visibility and traceability. Many enhancements to existing materials handling and storage solutions based on this increased accuracy of data have been proposed – we refer the interested reader to the numerous business case reports on www.autoidcenter.org or for manufacturing applications (McFarlane et al, 2002), supply chain management (McFarlane et al, 2002b), retail (Sydalio, 2002) and product life cycle management (Bajic, 2002). These enhancements make little or no alteration to the respective closed loop discrete event control system. We note, however, that the potential impact of the availability of product identity data can be potentially fundamental in closed loop industrial control

In Figure 1 we also include a networked control system which has direct access to the identity information generated in addition to other sensed information from the operating environment. The control system initiates actions based on the process and product identity information through appropriate commands to the actuators – see Figure 2. The issue of introducing data from automated identification systems into closed loop control environments and thereby enabling a greater customisation of control action has previously been discussed in McFarlane (2002). It is the fact that collection of product identity data can be automated and used to uniquely identify a specific item in real time that is of most benefit when considering fundamental changes that automated identification might result in. It is this last characteristic that the remainder of the paper focuses on.

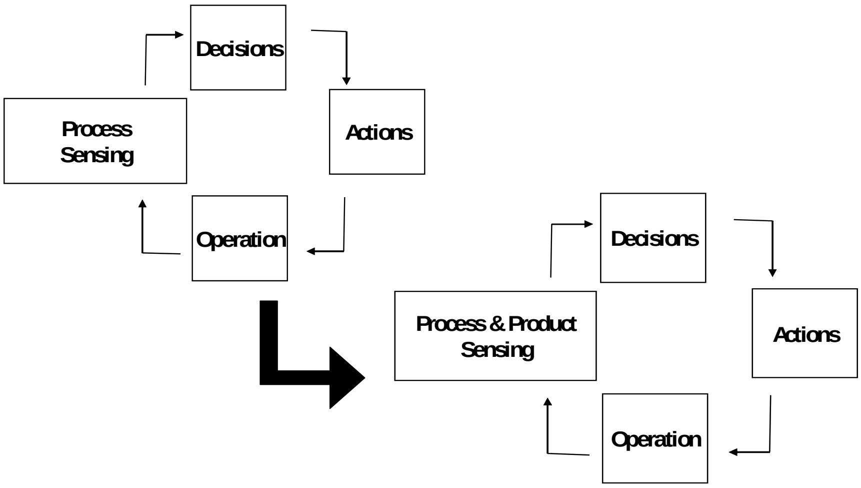

**Figure 2 General Impact of Auto ID on Closed Loop Control**

## 3. Product Identity and Observability of Discrete Event Systems

### 3.1 Discrete Event Representations of Industrial Systems

Most of the operations in the manufacturing supply chain that involve the transformation or movement of individual products can best be described by a discrete event model (Ramadge and Wonham, 1989, Kumar and Garg, 1995, Cassandras and Lafortune, 1999). That is, we can represent the operation in terms of an sequence of its discrete states triggered by events which drive the transition from one state to another. In this paper we use a deterministic automata description as a means of describing (deterministic) discrete event behaviour taken from (Cassandras and Lafortune, 1999, Ch. 2).

**Definition 3.1** [Deterministic Finite-State Automaton – Cassandras and Lafortune, 1999]

A deterministic automaton $G$ is defined as

$$G = (X, E, f, \Gamma, x_0, X_m) \qquad (3.1)$$

where
- X is the finite set of states
- E is the finite set of events associated with the transitions between states in G
- $f : X \times E \to X$ is the transition function
- $\Gamma : X \to 2^E$ is the active or feasible event function
- $x_0$ is the initial state
- $X_m \subseteq X$ is the set of marked state

Note:
(i) Such a description can be used to model a material transformation or transportation process where – for example - $X$ denotes the set of processing steps for a product.
*(ii)* The marked states, $X_m$, represent the set of allowable termination conditions for the operation – e.g. the completion of a production operation or a completed materials handling operation.

We also define for completeness the languages generated and marked by $G$

**Definition 3.2** [Languages Generated and Marked by *G* – Cassandras and Lafortune, 1999]

The language *generated* by *G* in (3.1) is given by

$$L(G) = \{s \in E^* : f(x_0, s) \text{ is defined}\} \qquad (3.2)$$

where *E** denotes the set of finite strings of events in *E*. The language *marked* by *G* is then given by

$$L_m(G) = \{s \in L(G) : f(x_0, s) \in X_m \text{ is defined}\} \qquad (3.3)$$

Hence the language *L(G)* represents all possible sequences of events that can be generated from the initial state condition $x_0$ and $L_m(G)$ represents the subset of those sequences which terminate on the marked states of *G*. Following the convention in (Lin and Wonham, 1990), we assume for the remainder of this paper that $L_m(G) = L(G)$ and $L(G) \neq 0$ which means that there are no blocking conditions associated with *G* which stop the system from reaching a terminal state.

### 3.2 The Set of Observable Discrete Event States

In the design of supervisors for discrete event system, it is critical to be able to identify the subset of the event set *E* which corresponds to events for which there are *observations* which enable the supervisor to be able to detect the onset of the event (and hence prepare to take appropriate control action). Defining the observable (resp. unobservable) event set by $E_o$ (resp. $E_{uo}$) we note that

$$E = E_o \cup E_{uo}$$

and we define the observability mask or projection *Po* of the states of *G* onto the set that is observable by the supervisor by

**Definition 3.3:** [Observability Mask – Lafortune, 2000]

*The observability mask for G is a projection* $P_o : E^* \to E_o^*$ *mapping the (finite) event set of G onto the set of (finite) events* $E_o^*$ *observable by the supervisor.*

The result of such a mask, is to restrict the supervisor such that it can influence only $P_o[L_m(G)]$ of the possible sequences of events of *G* (see Figure 3). The restriction on the supervisory system as a result of a reduced set of observable event has been studied elsewhere (Lin and Wonham, 1990, Kumar et al, 1989) and is not within the scope of the current paper.

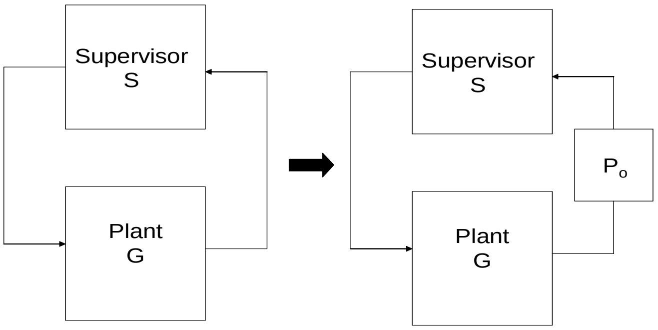

**Figure 3 Impact of Observability Mask on Supervisory Control**

### 3.3 Product Identity and Observability

We now restrict our analysis of discrete event models specifically to those representing physical supply chain operations. One interpretation of the impact of the product identity data in a supply chain context is that *without it*, there is a reduced observability of the (discrete-event) state space which represents the production, storage, transportation and retail processes that a product is subject to during its life cycle. In order to emphasise this, in the following analyses we are going to define a somewhat artificial partitioning of the event sets $E$ and $E^*$ in the following way:

**Definition 3.4** [Processing Operation and Product Type Events]

*Let the subscripts PO and PT denote events associated with processing operations and product type changes respectively. Then*

$$E = E_{po} \cup E_{pt}$$

$$E^* = E_{po}{}^* \cup E_{pt}{}^*$$

*where event sets* $E_{po}, E_{pt}$ *(respectively* $E_{po}{}^*, E_{pt}{}^*$*) represent the events in E (resp. E*) associated with processing operations and the changing of a product type – without the execution of any processing operations*

The class of product type “events” is clearly artificial as it implies that a product type can be changed independently of processing operations.

**Example 3.1**

The rationale for this partition is that it allows a very clear decomposition of events of the form

*Event A: {move product of type A from position X to position Y}*
*Event B: {move product of type B from position X to position Y}*

into events associated with process event detection and product type detection. Informally, we say that these events are *partially observable* with regular position sensing in that the transportation event can be observed even if it is impossible to distinguish whether a product of Type A or B has been moved. Using the formalism in Definition 3.4, we can rewrite these events as pairs of sub-events:

*Event A: {move product of type O from position X to position Y}, (change product of type O to product of type A) }*
*Event B: {(move product of type A from position X to position Y), (change product of type O to product of type B) }*

The observation of the second event in each case is clearly dependent on the availability of product identity data. Type O is the neutral or standard product type. Figure 4 illustrates the way in which this partitioning influences the state space. Usual finite automata notions apply. In case a) events $e_A$ or $e_B$ can only be distinguished (and hence observed) if product type sensing is available where the move takes place. Yet the movement of an item can be distinguished if there is some form of generalised proximity sensor available. In case b) where $e_o$ indicates the movement of the neutral product type and $e_A$ or $e_B$ indicate the sensing of product type, we see that $e_o$ is observable from a proximity sensor while $e_A$ or $e_B$ are unobservable.

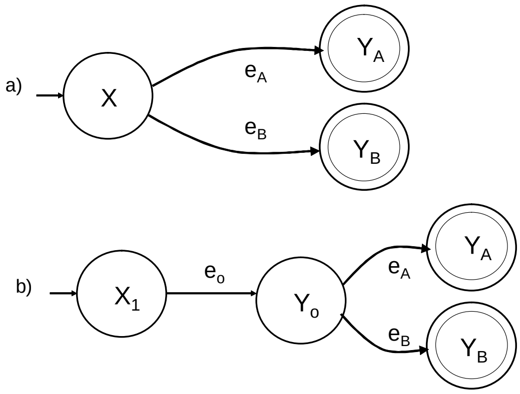

**Figure 4 Automata without (a) and with (b) partitioning of event types**

We now make a relatively straightforward observation which is the main contribution of this paper:

**Definition 3.5** [Full Operational Observability]

*Let the event set* $E_{po}$ *be partitioned* $E_{po} = E_{po\_o} \cup E_{po\_uo}$ *where* $E_{po\_o}, E_{po\_uo}$ *refer to the observable and unobservable event sets respectively. A plant G is fully operationally observable if and only if* $E_{po} = E_{po\_o}$ *and* $E_{po\_uo} = \{\varepsilon\}$ *where* $\{\varepsilon\}$ *denotes the empty set of empty string,* $\varepsilon$.

**Theorem 3.1** [Product Type Observability]

*Assume that G is fully operationally observable. Let the event set* $E_{pt}$ *be partitioned such that* $E_{pt} = E_{pt\_o} \cup E_{pt\_uo}$ *where* $E_{pt\_o}, E_{pt\_uo}$ *refer to the observable and unobservable event sets respectively. A fully operationally observable plant G is observable with respect to product type if and only if* $E_{pt} = E_{pt\_o}$ *and* $E_{pt\_uo} = \{\varepsilon\}$.

The next result directly follows from this theorem.

**Corollary 3.1** [Product Type Observability Mask]

*Assume that G is fully operationally observable. The product type observability mask for G is a projection* $P_{po} : E_{po}^{*} \cup E_{pt}^{*} \rightarrow E_{po}^{*}$ *mapping the (finite) event set of G onto the set of (finite) events* $E_{po}^{*}$ *observable by the supervisor.*

**Remark 3.1**

Theorem 3.1 and Corollary 3.1 essentially state that to fully observe the state space of *G* we require both process operational (proximity) data in conjunction with product type data. In fact the requirement is rather more subtle than this in that many automated product type sensing devices – such as RFID systems - are directionally agnostic in that they sense information within a read range without sensing the direction it comes from. In order to truly observe the state space defined by both process operations and product types it is in fact necessary to determine both location and identity information in a coordinated manner

**Remark 3.2**

The implication of these results is the following. For any operational state of $G$ there exists $n+1$ possible variants if there are $n$ product types under consideration. Alternatively, this can be viewed as $n$ separate states associated with the operational state. This can represent a significant inflation of the state space in many industrial circumstances, and the presence of product identity sensing can greatly enhance the observability of such systems.

**Remark 3.3**

We noted in Section 2 that Auto ID systems are in fact capable of identifying not only product type but also the unique identity of an item. The results in this section extend in a straightforward manner for the case when both the product type and its unique identity can be identified. In fact this case, can simply be considered to be that of a *one of a kind* type operation in which each product is of a different type to its predecessor.

# 4 Illustrative Example – An Industrial Storage Buffer

## 4.1 Overview

By way of example, we now consider storage of products within a prototype customised packing cell that has been developed in the Institute for Manufacturing at Cambridge University Engineering Department as a demonstration system for the Auto ID Center and its industrial sponsors. The cell in Figure 5 shows individual retail items arriving in a random sequence on the left conveyor, being identified then stored or directly packed into a customised “gift box” whose identity is linked to a set of instructions which directly drive the control operation. This system is described in significant detail in (Hodges et al, 2002).

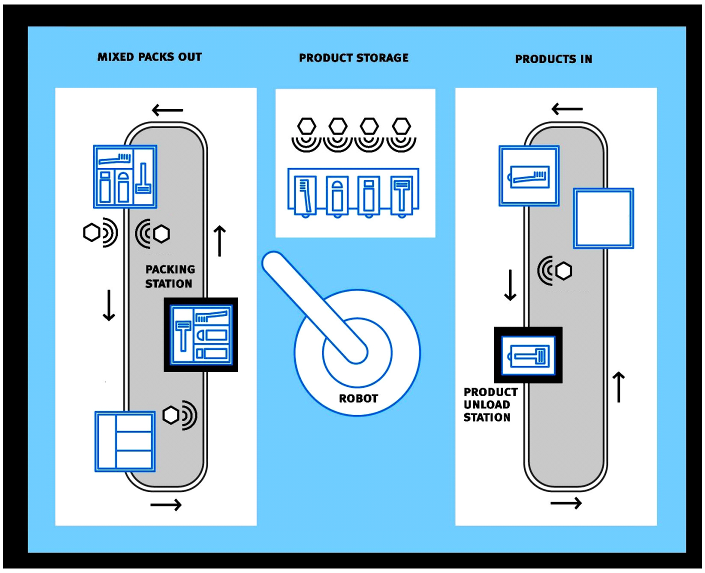

**Figure 5 Schematic of Prototype Customised Packing Cell**

**Figure 6 Product Storage System in Prototype Customised Packing System**

This example focuses specifically on the simple addition to and removal of items from the product storage zone which is illustrated in Figure 6. We note that the exit from each first-input, first-output (FIFO) storage "stack" is viewed by an RFID reader and in addition, any item entering any one of the stacks is also read by an additional RFID reader (not shown). We also note that due to gravity, the stacks always fill from the bottom up.

### 4.2 Modelling and Analysis

We simply aim here to show the impact product identity information has on the observability of the state of any one of the product stacks. Initially, consider Figure 7 (a) in which there is only one type of product being loaded and unloaded and where there is a proximity sensor at both input and output.

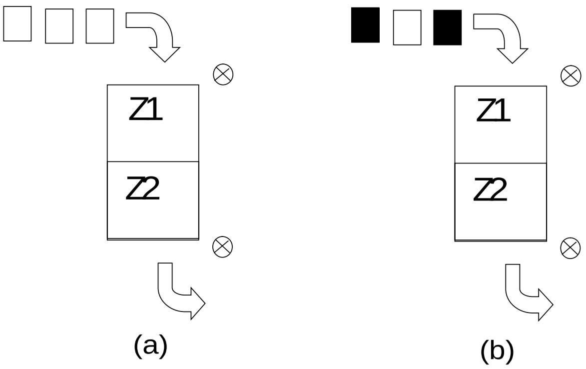

**Figure 7 Schematics of Product Storage Stack**

The states of this system are defined in terms of entries in positions $Z_1$ and $Z_2$ and the event set given by $E=\{e_1,e_2,e_3\}$ where $e_1$ denoted the addition of an item, $e_2$ denoted the removal of an item and $e_3$ denoted the simultaneous addition and removal of items. The automaton representing this system is given in Figure 8 in which each state – representing 0 items, 1 item and 2 items respectively – is marked as a potential terminal state. The important point is that each of the events in $E$ are observable via the pair of proximity sensors.

Turning now to case (b) in Figure 7 we now must consider two types of products arriving. If we define the white product as the neutral product in Figure 4, the resulting set of events $E=\{e_1,e_2,e_3,e_4\}$ can be defined by

$e_1$ – add neutral item to the top of the stack

$e_2$ – remove neutral item and add black item to place $z_1$
$e_3$ – remove neutral item from the bottom of the stack
$e_4$ – remove black item and add neutral item to place $z_2$

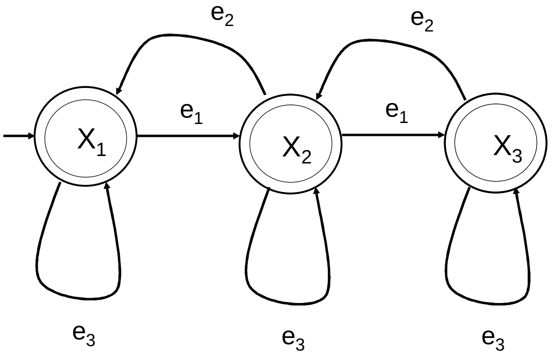

**Figure 8 Automaton Model for Single Product Type**

An automaton model for this system is given in Figure 9. (Further details on the model development will be provided in the full paper.)

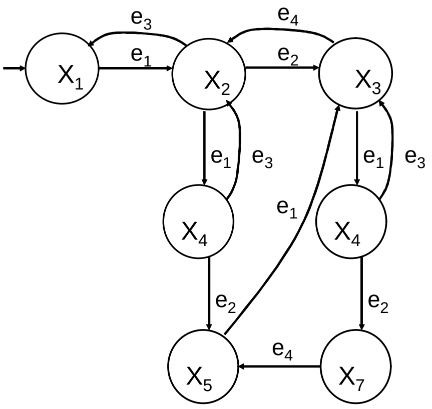

**Figure 9 Automaton Model for Multiple Product Types**

Considering this model we note that with proximity sensing alone, events $e_2$ and $e_4$ are unobservable as per the arguments in Example 3.1. Hence although the system is Fully Operationally Observable it is not Product Type Observable. With product identity sensing in place of the simple proximity sensors the system is now Product Type Observable. This is summarised in the table below:

| **Sensor Type** | $E_{po\_o}$ | $E_{po\_uo}$ | $E_{pt\_o}$ | $E_{pt\_uo}$ |
|---|---|---|---|---|
| **Proximity Sensors** | $\{e_1, e_3\}$ | $\{\varepsilon\}$ | $\{\varepsilon\}$ | $\{e_2, e_4\}$ |
| **Identity Sensing** | $\{e_1, e_3\}$ | $\{\varepsilon\}$ | $\{e_2, e_4\}$ | $\{\varepsilon\}$ |

**Remark 4.1**

Although not discussed in detail in this paper, the implications of the addition of product identity sensing on supervisory control of such a discrete event system are immediately clear and quite far reaching. The ability to customise production or materials handling operations is known to be directly linked to the flexibilities of the corresponding equipment required to carry out the task. Less well understood yet equally important is the issue dealt with in this paper, namely, without product identity sensing it is immaterial whether flexible equipment is available or not! In the case of a single product stack, the use of RFID sensors is perhaps excessive given the FIFO nature of the storage device – i.e.

there is insufficient flexibility in the equipment to warrant the fidelity of sensing. However, when four stacks are used simultaneously there is sufficient cause for such sensing. This relationship between this behaviour and supervisory control performance will be the subject of a further paper (McFarlane, 2002c)

## 5. Acknowledgements

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